

Weighing in: Contribution of ocean mass changes to sea level

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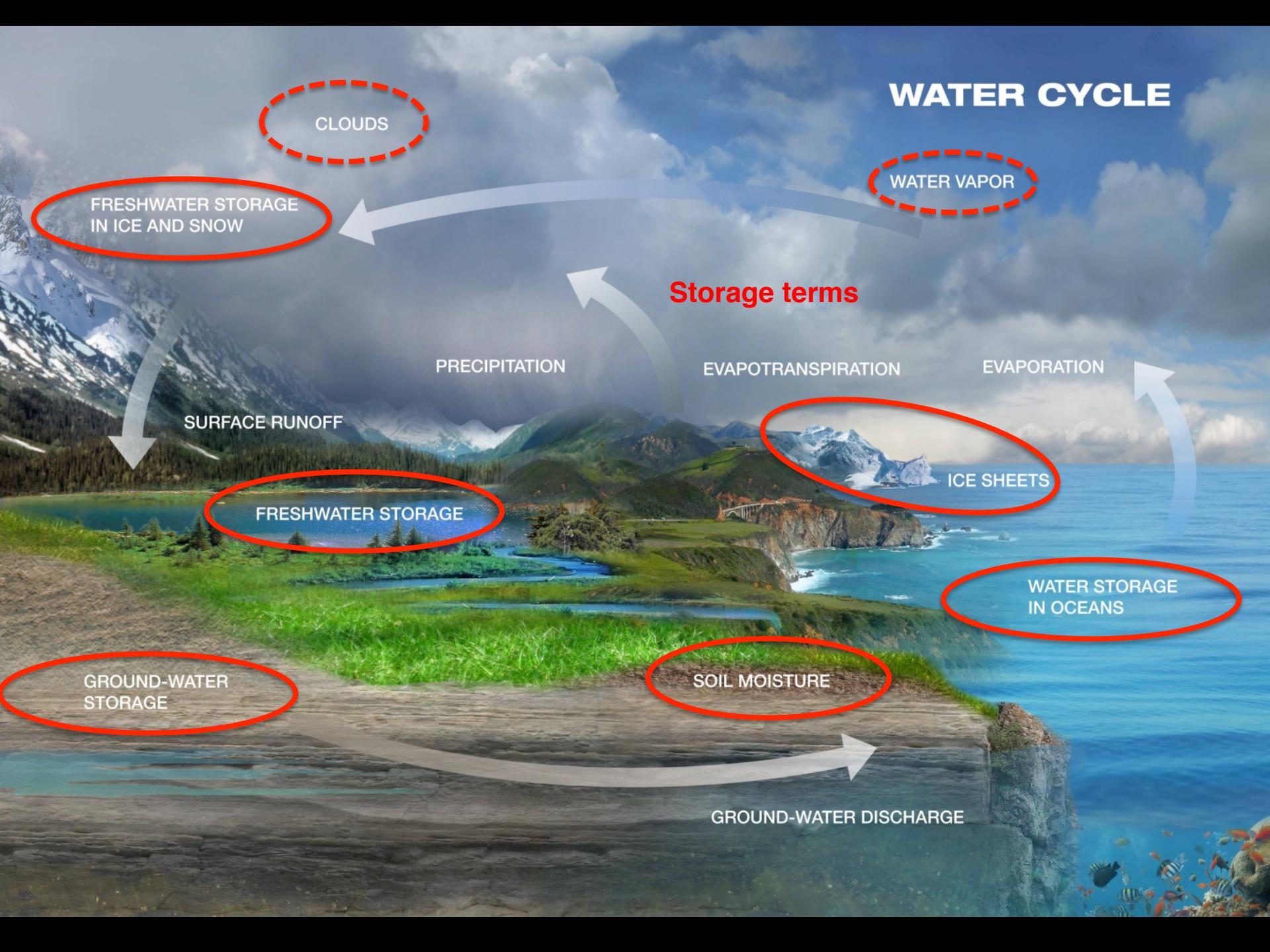
thanks for discussions with:
D. Chambers, S. Nerem, D. Wiese, A. Gardner, M. Watkins,
X. Wu, C. Boening, R. Ponte, J. Wahr, I. Velicogna, E. Ivins, S.
Adhikari, B. Hamlington, P. Thompson, M. Tamisiea, J.
Kusche, R. Rietbroek... and many others!

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(very) High Level Summary



WATER CYCLE



Sea level budget

Hydrological budget

Barystatic sea
level

Ocean mass

Thermosteric
sea level

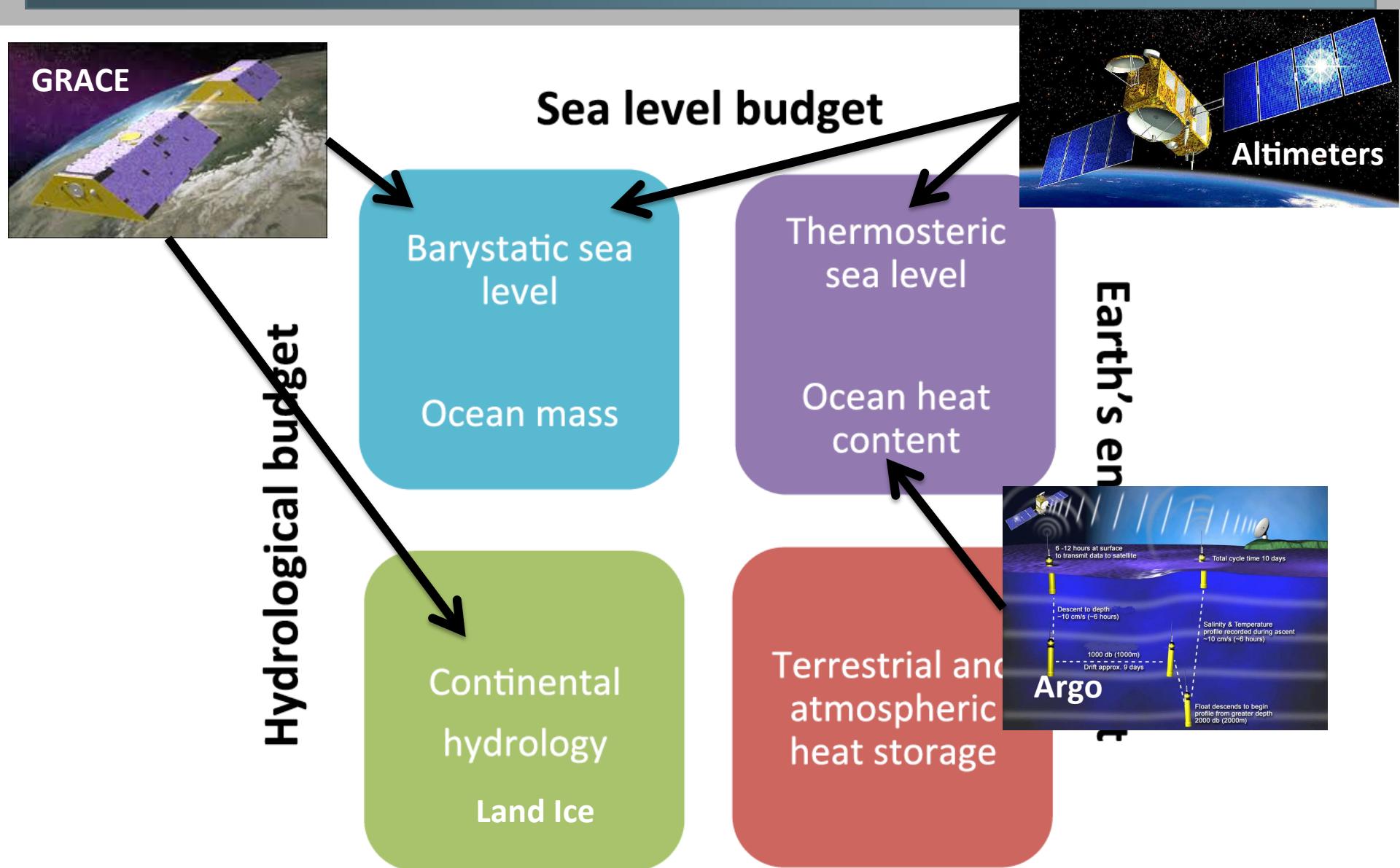
Ocean heat
content

Continental
hydrology

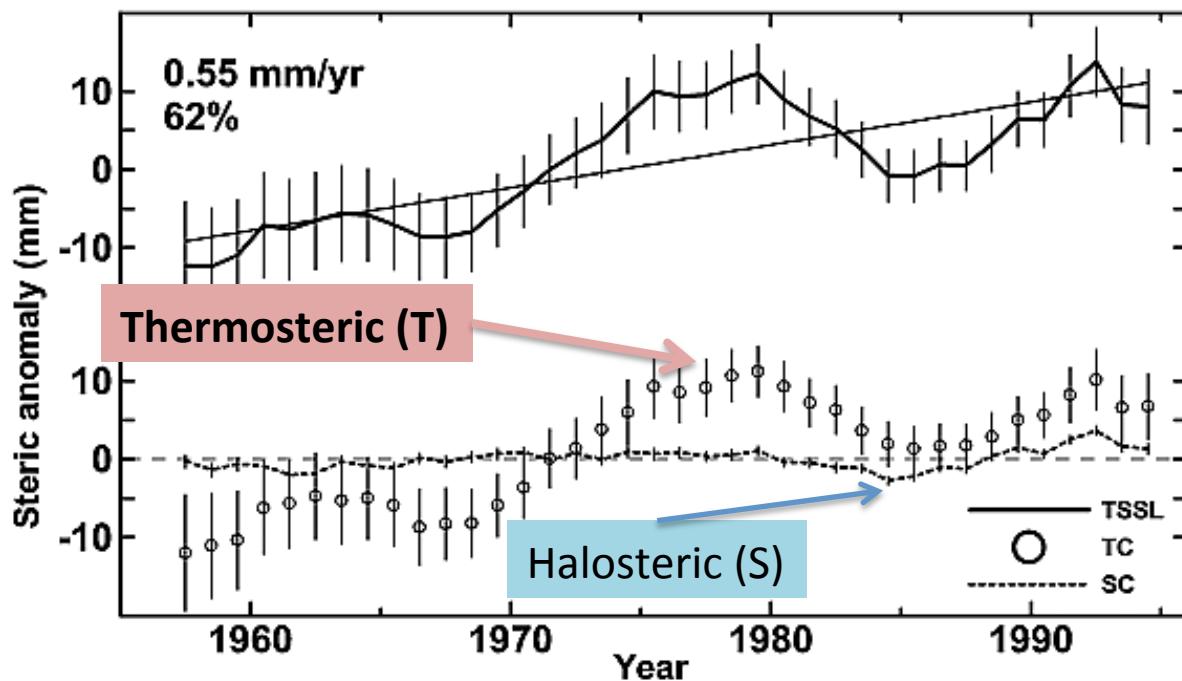
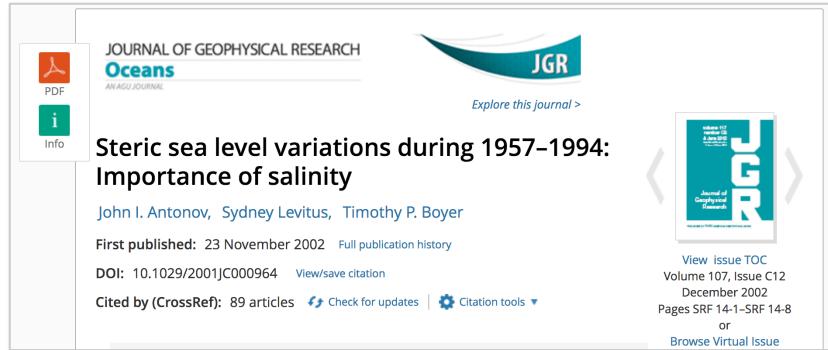
Land Ice

Terrestrial and
atmospheric
heat storage

Earth's energy budget



From ocean freshening to ocean mass



[Antonov, 2002]

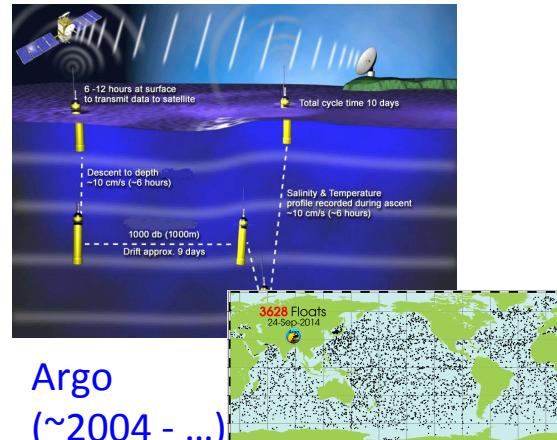
- Halosteric trend order of magnitude less than trend from thermal expansion.
- ‘Munk factor’: Halosteric trend requires **~500 km³** of fresh water to be added to the world ocean every year for the 1957–1994 period.
- Freshening would require a mean sea level rise of **$1.35 \pm 0.50 \text{ mm/yr}$** , in addition to the steric changes.
- IPCC AR4: “error in estimates mass changes derived from salinity [] is too large to provide useful constraints on the sea level change budget”

Sea Level Rise (SLR) Budget

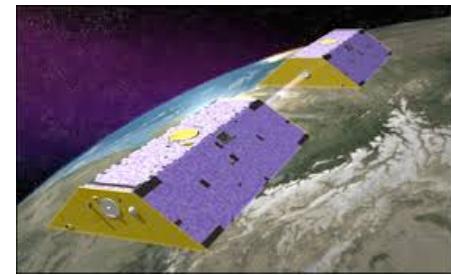
$$\Delta \text{SLR}_{\text{total}} = \Delta \text{SLR}_{\text{steric}} + \Delta \text{SLR}_{\text{mass}}$$



Jason-1&2, T/P, Envisat
(1993 - ...)



Argo
(~2004 - ...)



GRACE (2002-...)
GRACE-FO (2018 ...)

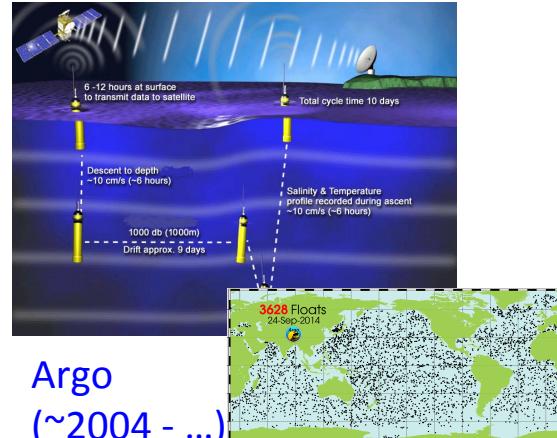
$$\Delta \text{SLR}_{\text{total}} = \Delta \text{SLR}_{\text{steric}(0-2000m)} + \Delta \text{SLR}_{\text{mass}}$$

Sea Level Rise (SLR) Budget

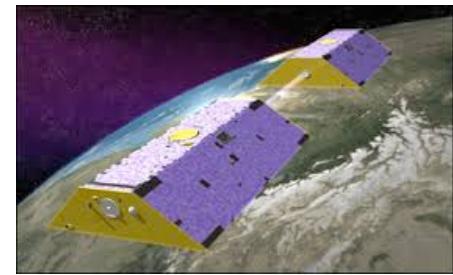
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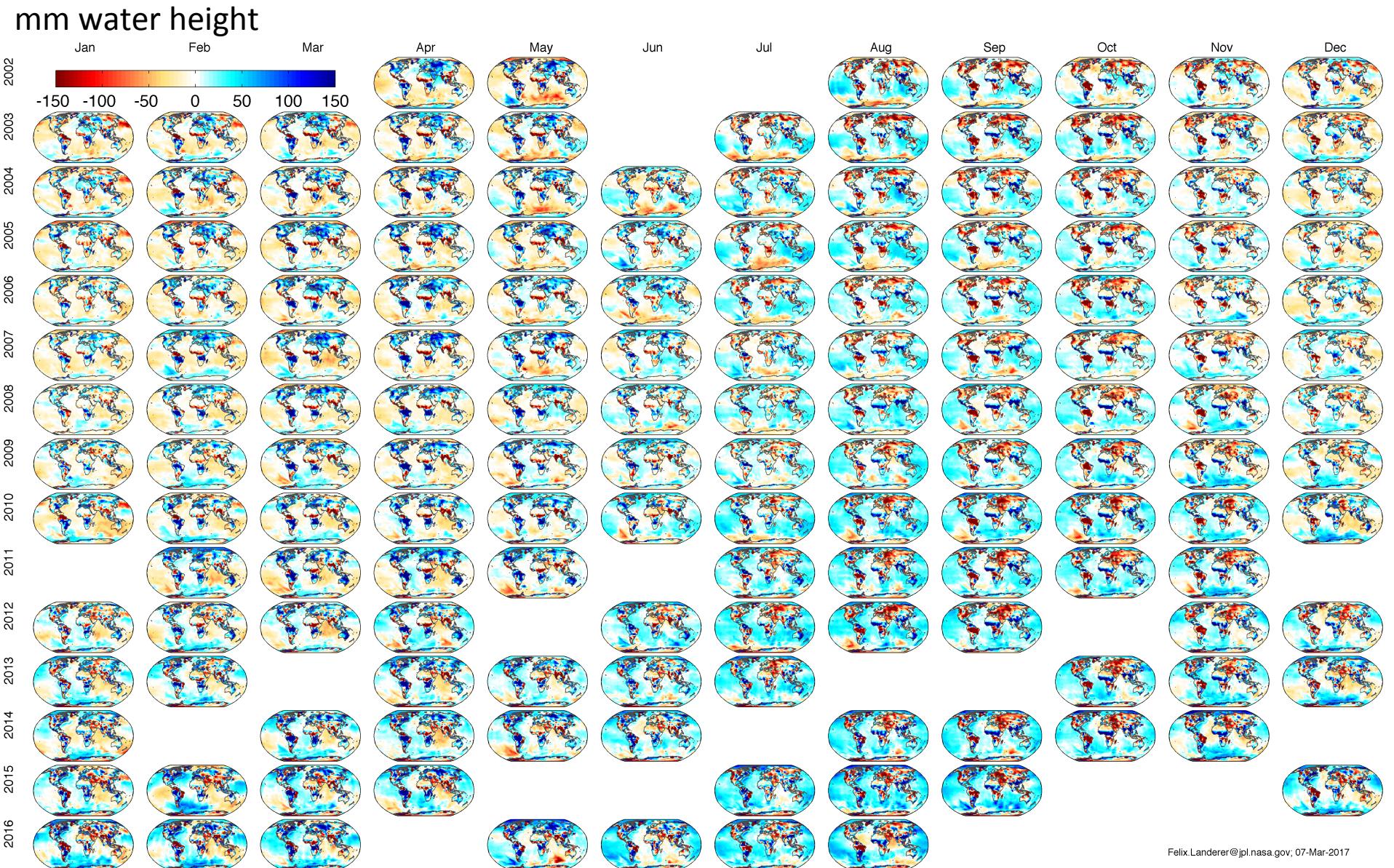


GRACE (2002-...)
GRACE-FO (2018 ...)

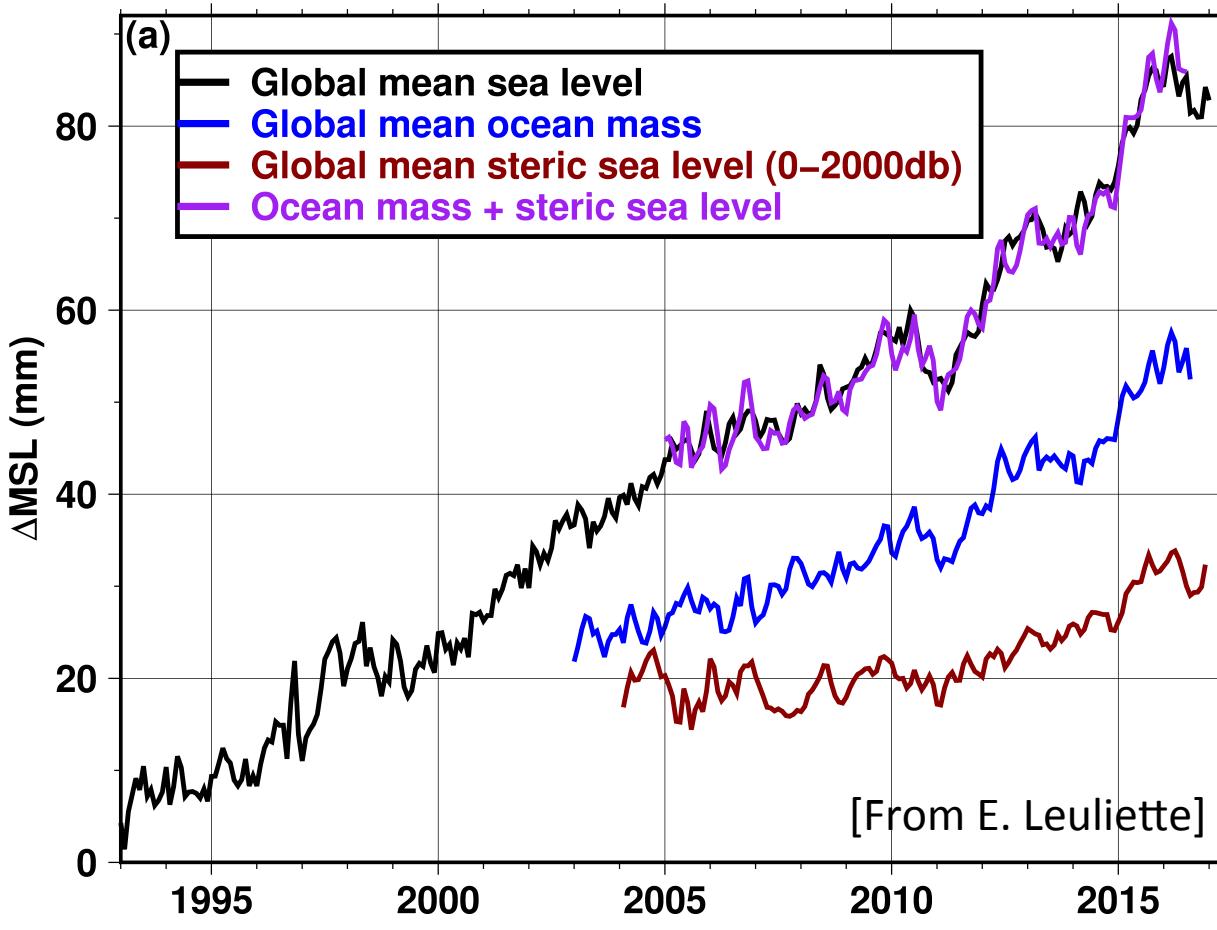
$$\Delta \text{SLR}_{\text{total}} = \Delta \text{SLR}_{\text{steric}(0-2000m)} + \Delta \text{SLR}_{\text{mass}}$$

+ Residual ($\Delta \text{SLR}_{\text{steric}(<2000m)}$)
+ Errors(Random, Biases)

Direct observation of mass change: GRACE (2002 –)



Sea Level Budget: global mean



15-year trend:

- 1/3 from steric
- ‘budget closure’: $\text{mass} + \text{steric} = \text{total}$
- little room for a large deep ocean warming contribution
- systematic trend biases still large $O(0.4 \text{ mm/yr})$
 - GIA
 - Geocenter
- positive acceleration emerging
- deep ocean warming?

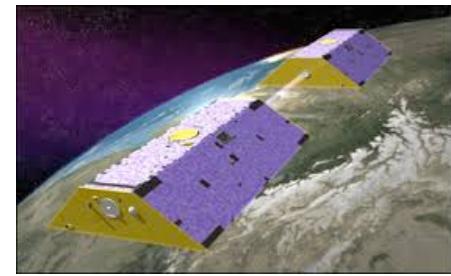
see these posters for further details:
[E. Leuliette & S. Nerem]

Sea Level Rise (SLR) Budget

$$\Delta \text{SLR}_{\text{total}} = \Delta \text{SLR}_{\text{steric}} + \Delta \text{SLR}_{\text{mass}}$$

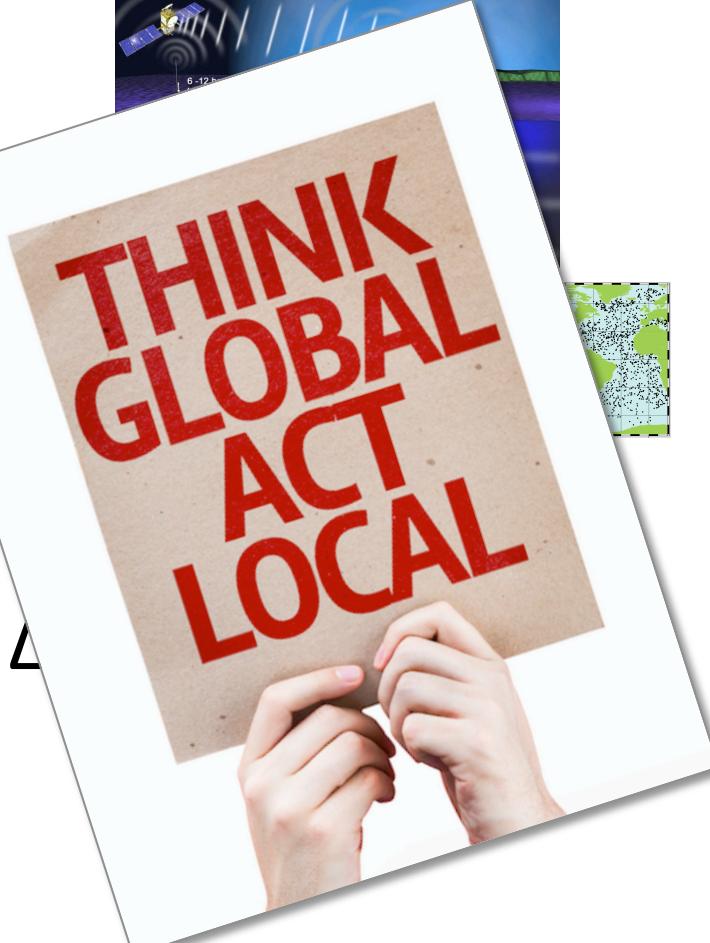


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(1993 - ...)



GRACE (2002-...)

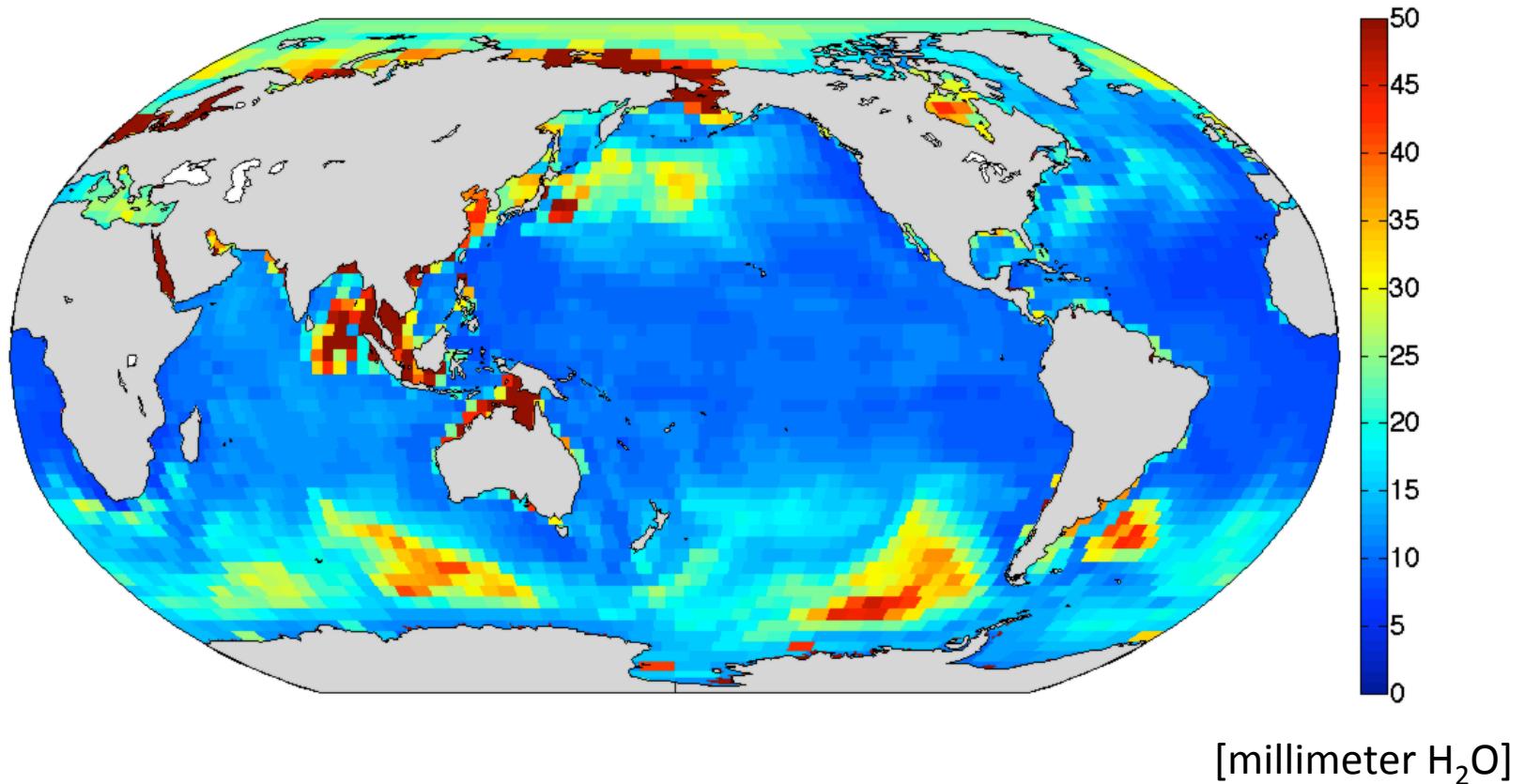
$$\Delta \text{SLR}_{\text{total}} = \Delta$$



$$\Delta \text{SLR}_{\text{mass}}$$

Variability of bottom pressure

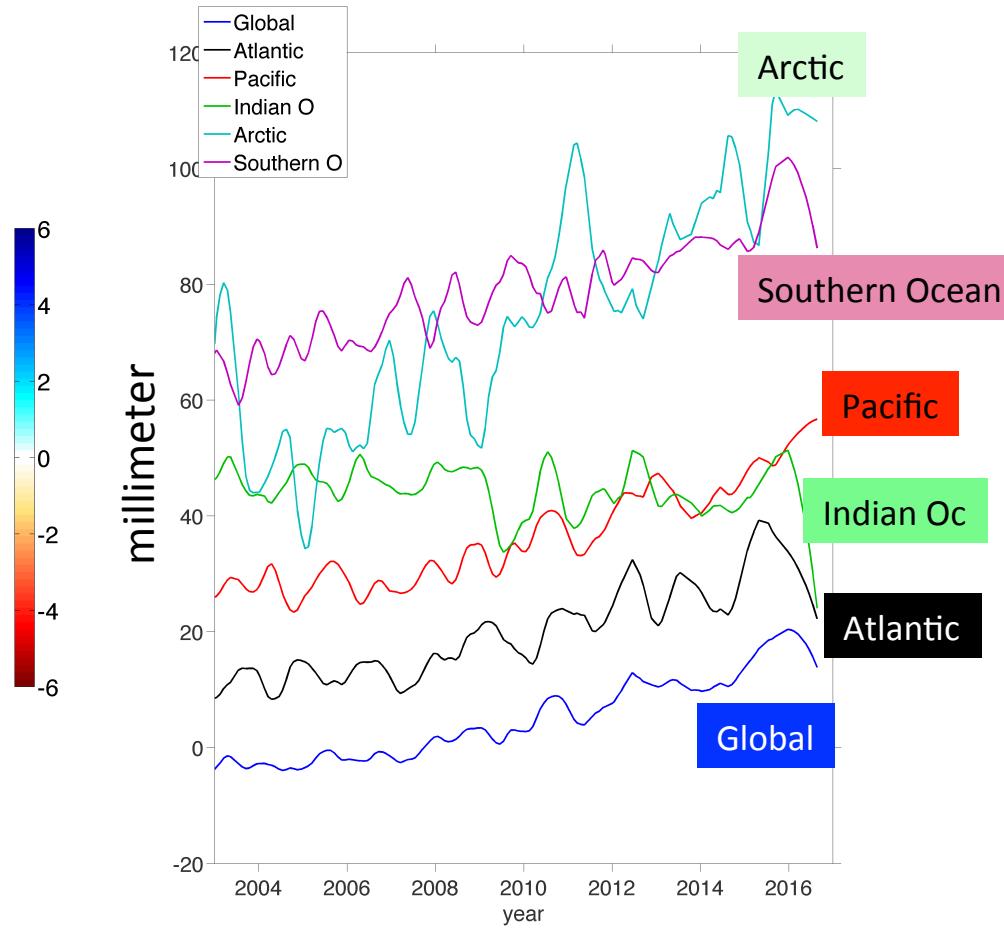
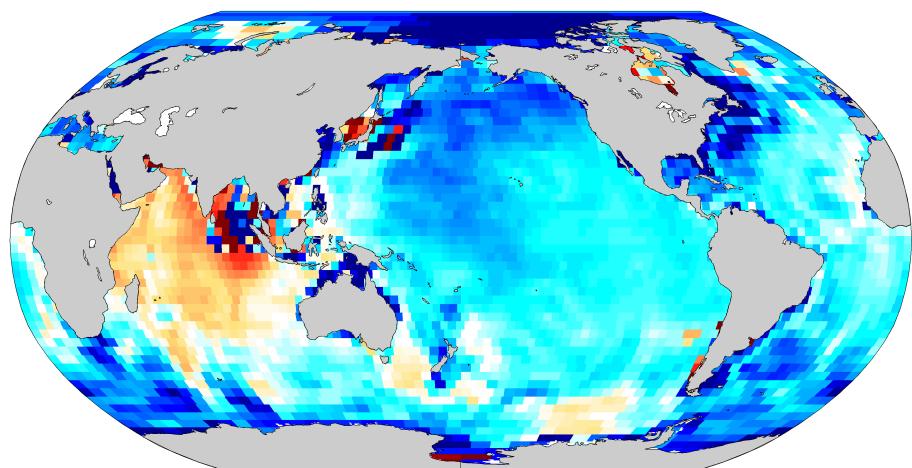
monthly RMS variability, seasonal cycle and trend removed



see [Piecuch & Ponte, 2011] for further details

Ocean mass changes (GRACE 2002-2016 trend): basin scales and spatial pattern

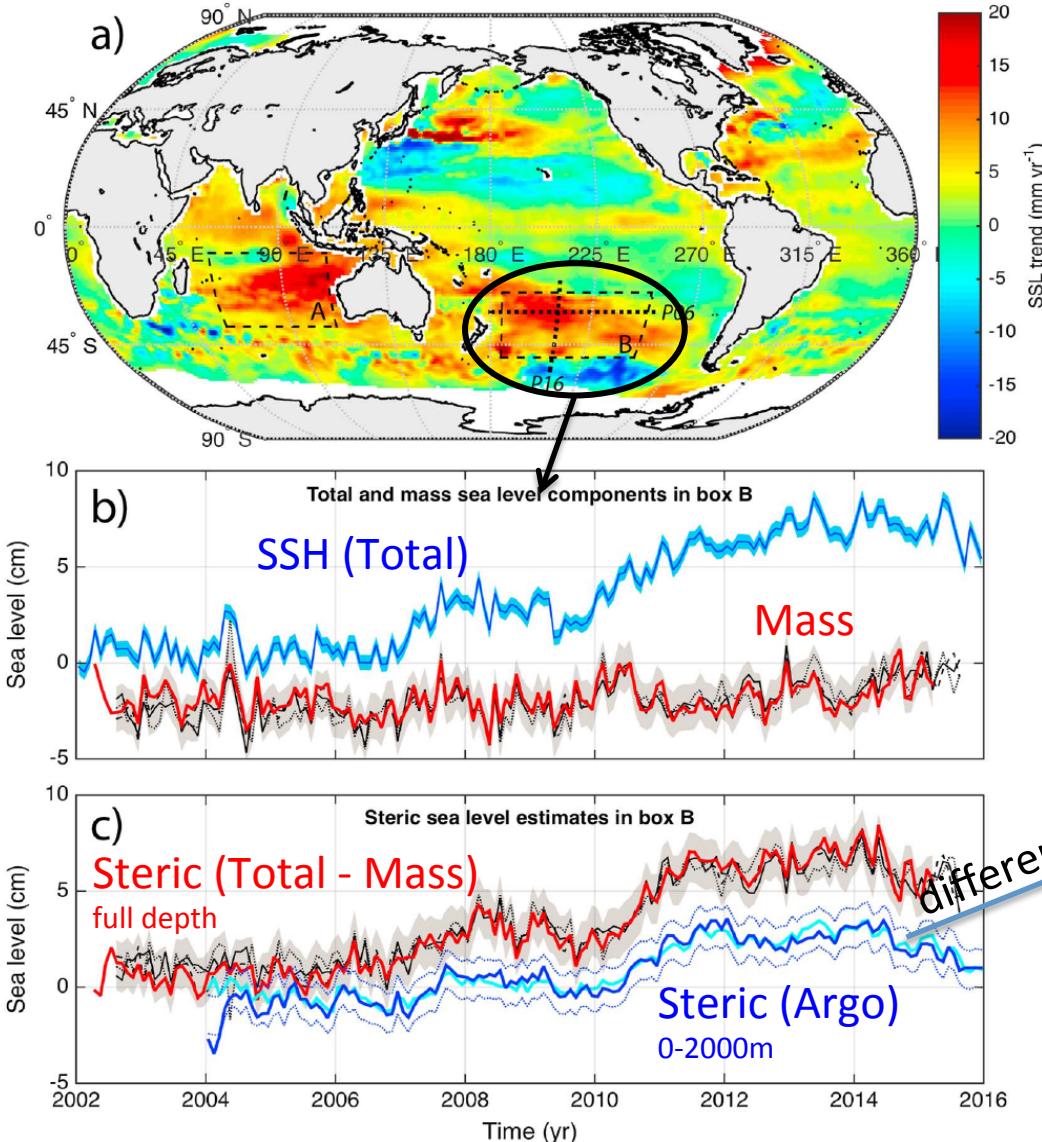
Bottom pressure trends [mm/yr]



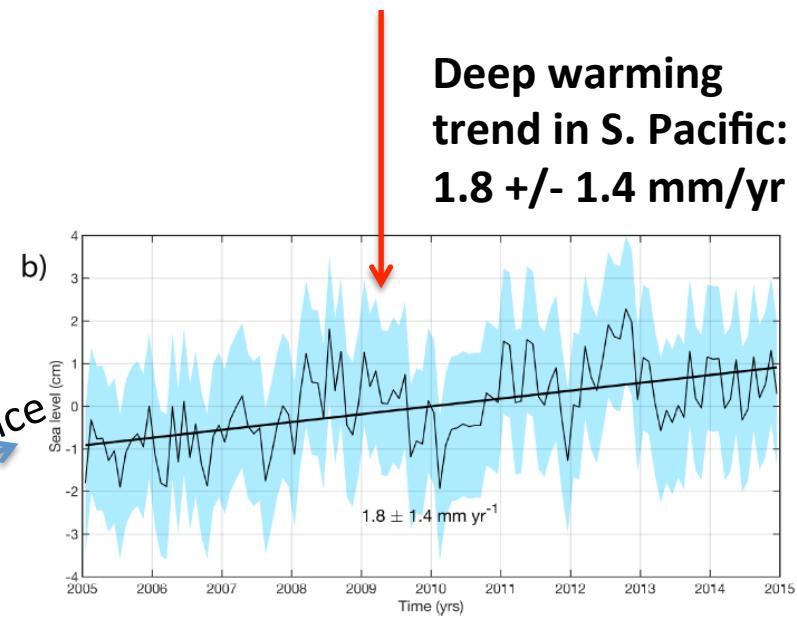
-> see poster by Eric Leuliette

Regional Sea Level Budget: deep warming

Altimeter – GRACE (= Steric)



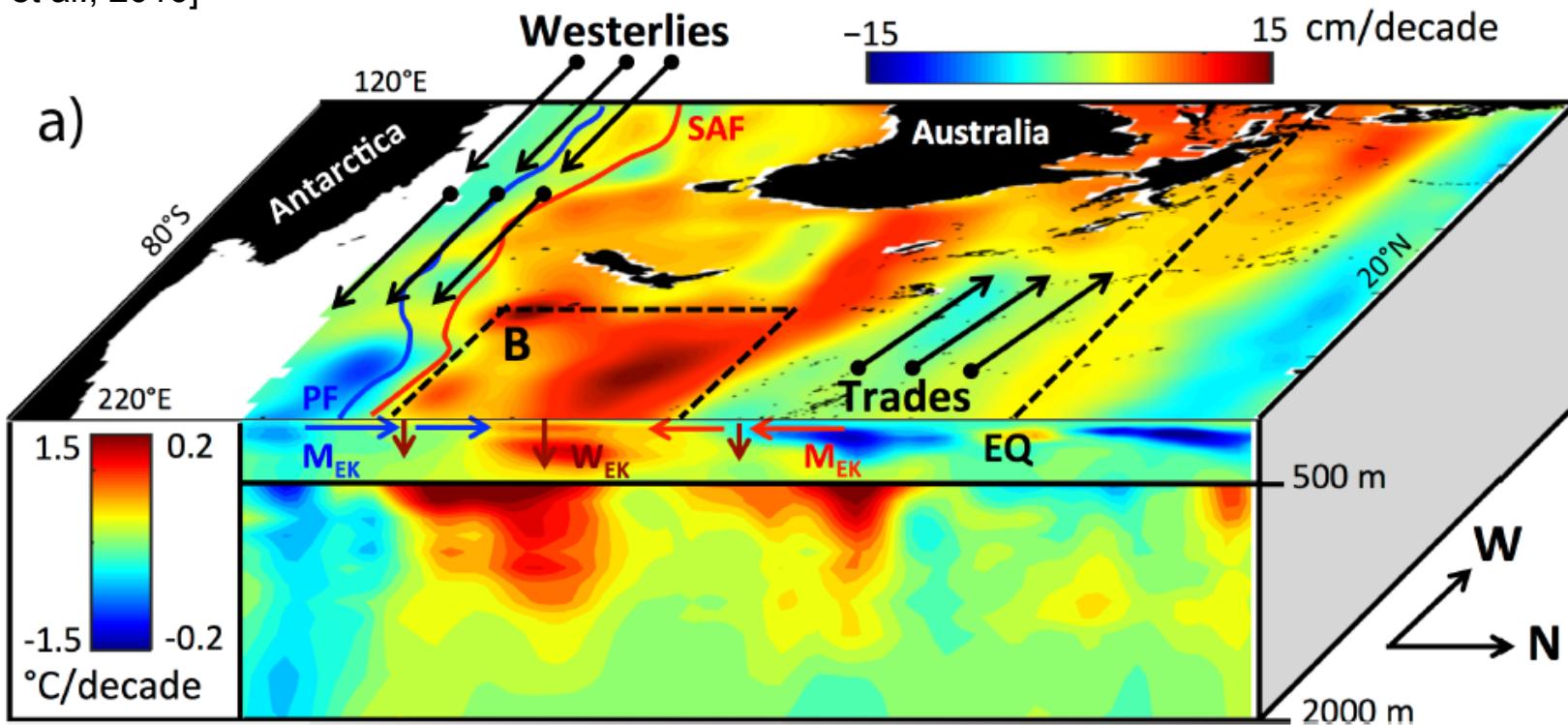
Satellite-based sea level trends over 2005–2014 from *density changes* alone (i.e., the mass contribution has been removed by subtracting GRACE observations from altimetry). Warm colors typically indicate ocean warming and expansion. The study region showed large **warming**, with a clear signal originating **below 2000m**.



[Volkov et al., 2016]
see also [Llovel et al., 2016]

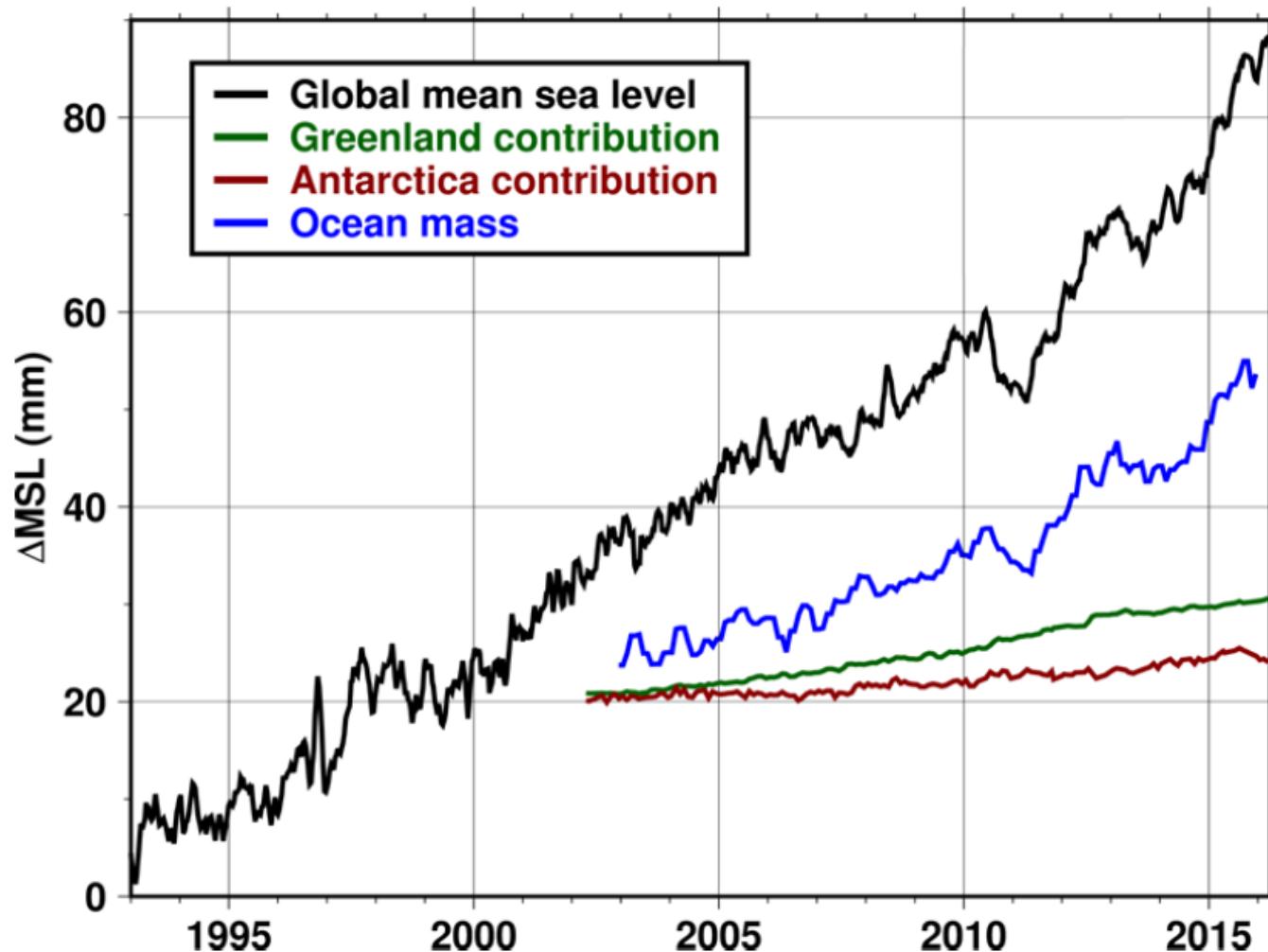
Regional Sea Level Budget: deep warming

[Volkov et al., 2016]

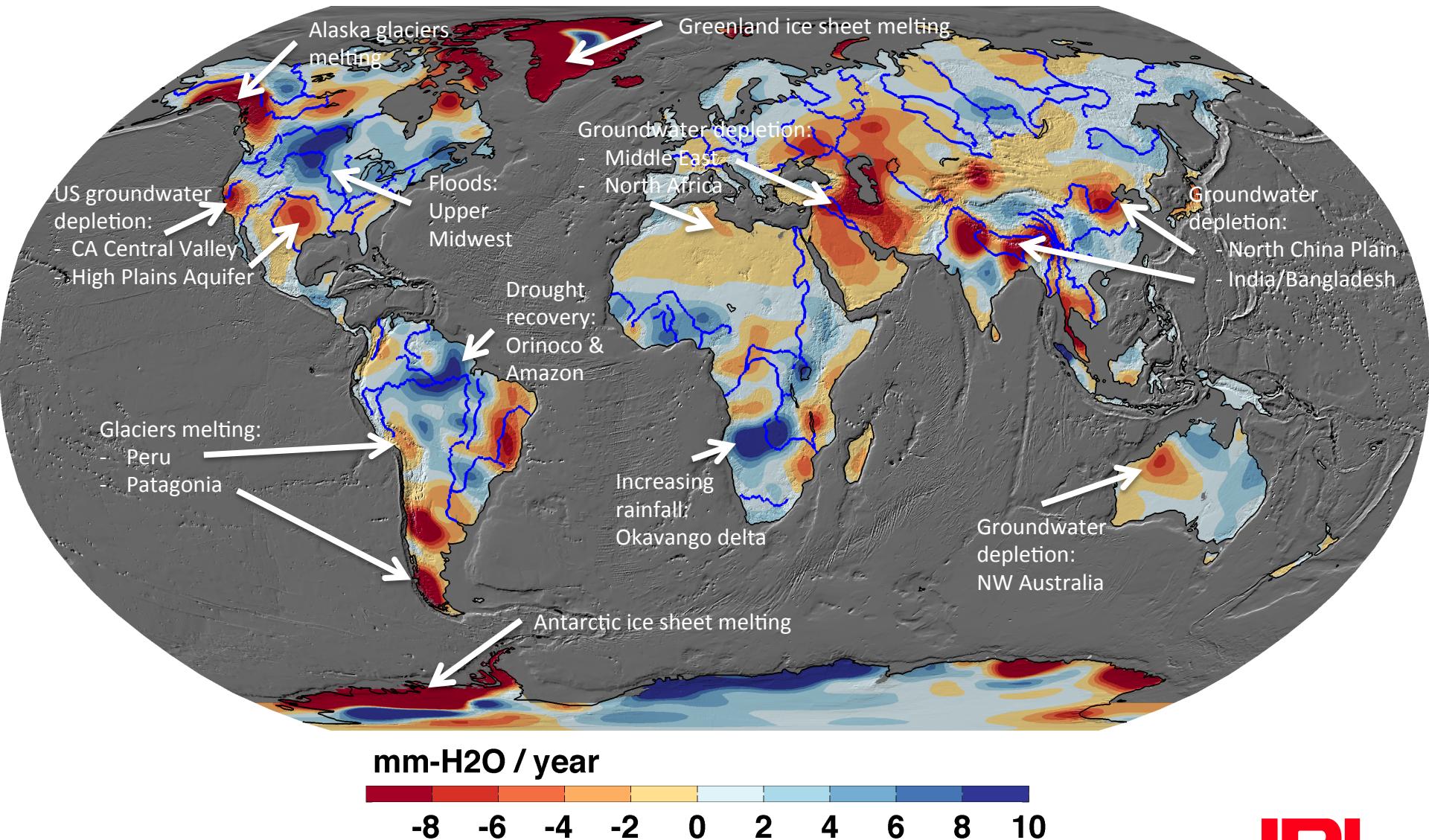


- Westerly winds over the Southern Ocean and easterly trade winds in the tropics drive Ekman transports that converge in the subtropical South Pacific.
- Strengthening of the wind stress curl in 2005-2014 led to an intensification of downward Ekman pumping with a local maximum within the dashed box. Note that the temperature scale is split between the upper 500 m and 500-2000 m.

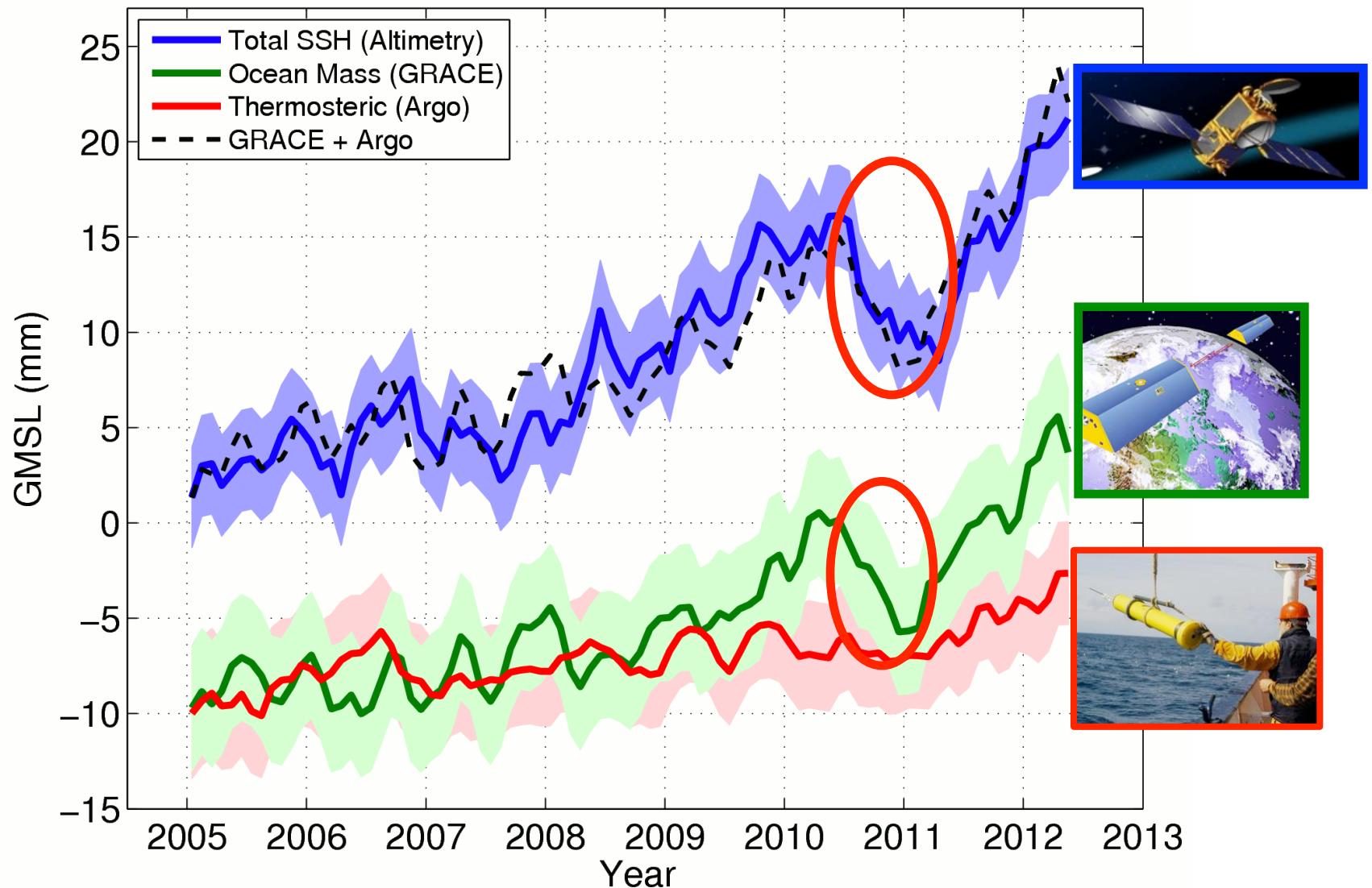
Back to the global budget: mass sources



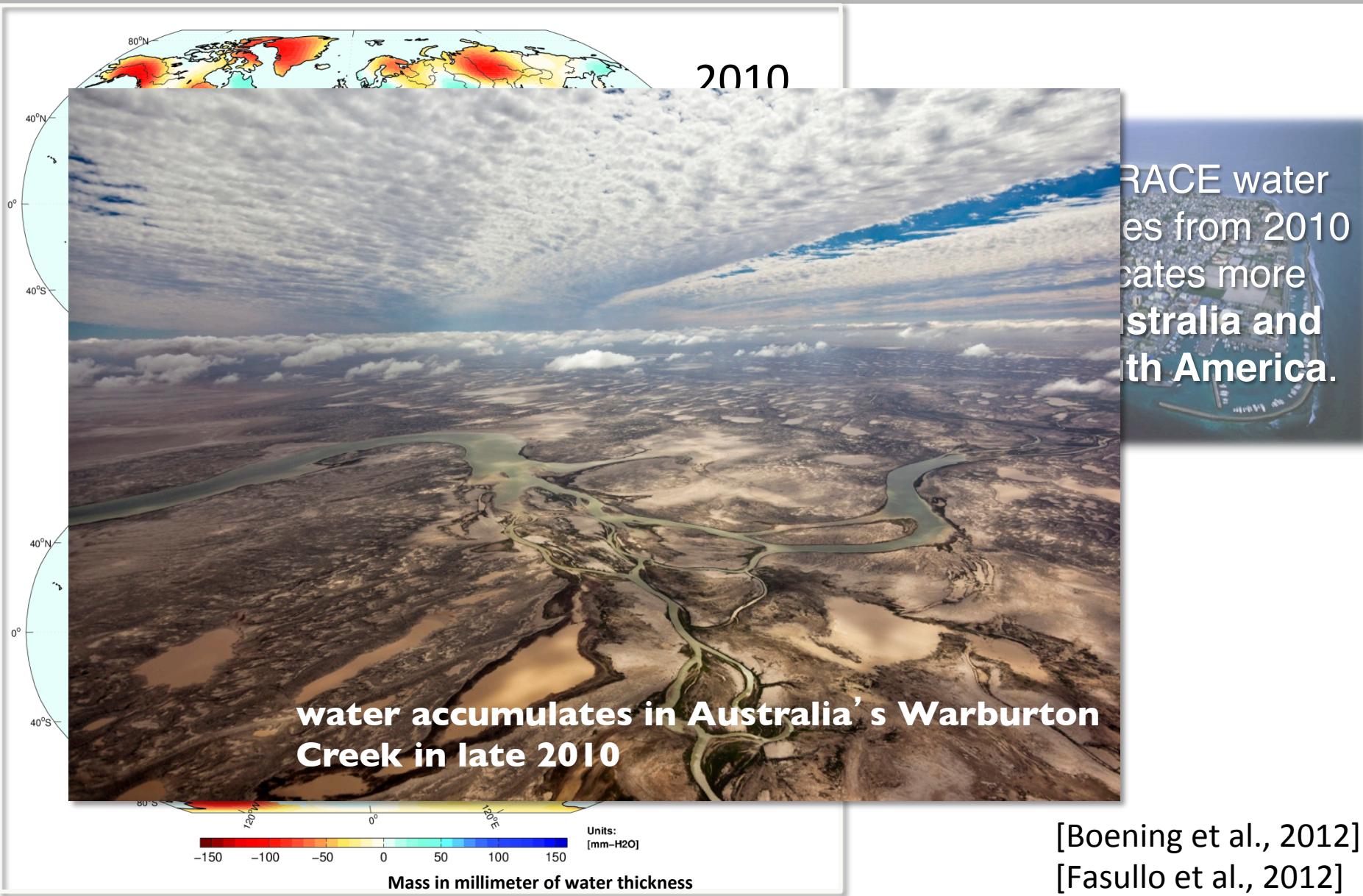
Sources of Ocean Mass Change: Global Water Storage & Land Ice changes observed by GRACE (over 2002-2015)



The 2010/2011 ‘Sea Level Drop’



The 2010/2011 ‘Sea Level Drop’



Glacier & Land hydrology contributions

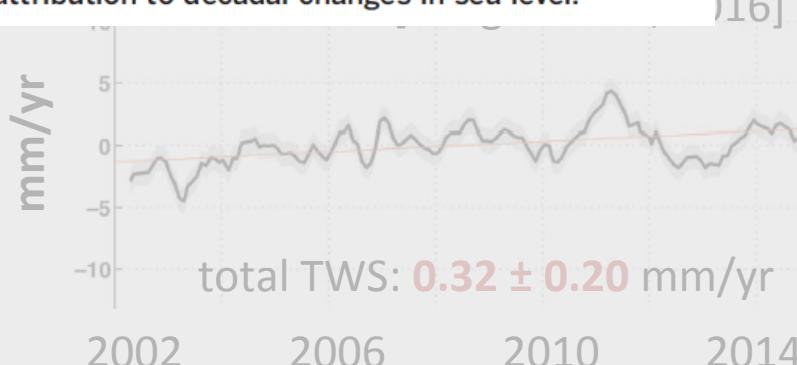
GLOBAL WATER CYCLE

A decade of sea level rise slowed by climate-driven hydrology

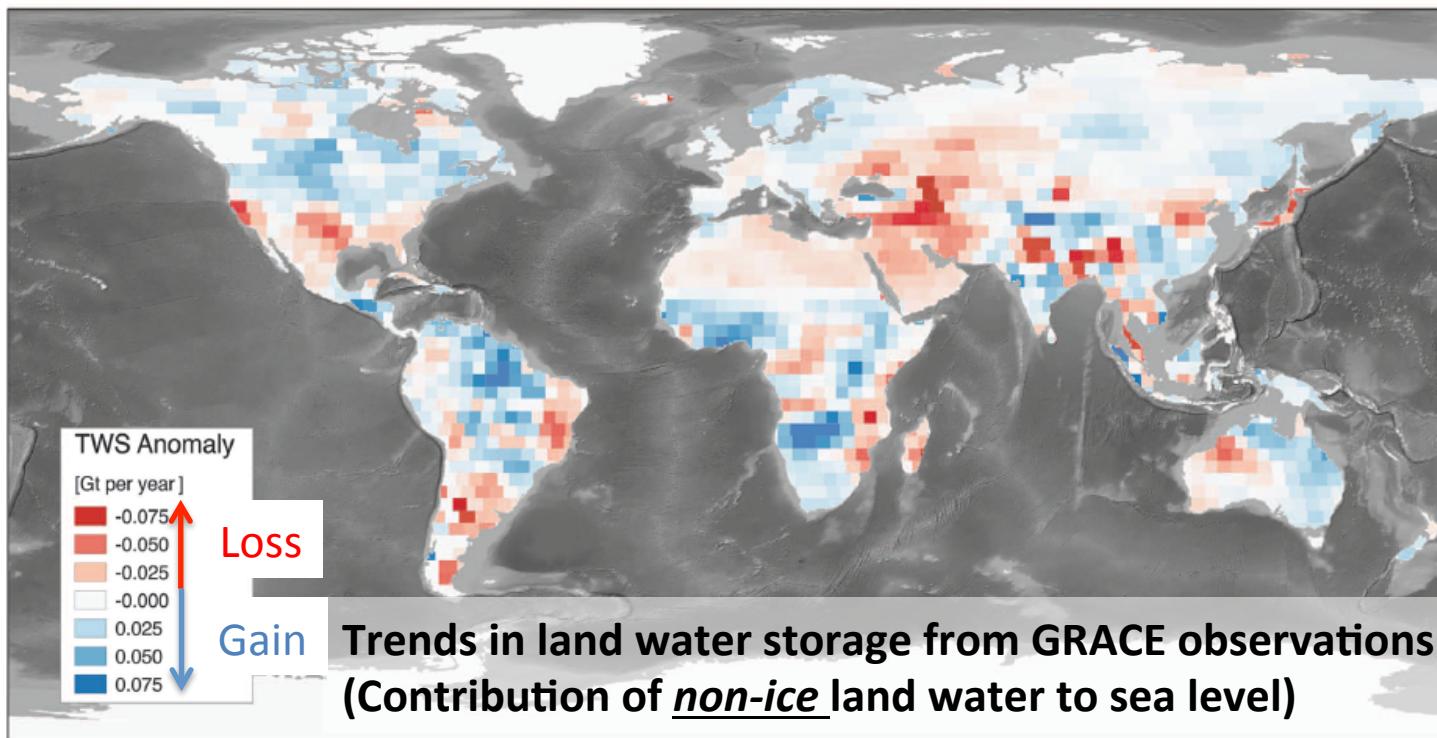
J. T. Reager,^{1*} A. S. Gardner,¹ J. S. Famiglietti,^{1,2} D. N. Wiese,¹ A. Eicker,³ M.-H. Lo⁴

Climate-driven changes in land water storage and their contributions to sea level rise have been absent from Intergovernmental Panel on Climate Change sea level budgets owing to observational challenges. Recent advances in satellite measurement of time-variable gravity combined with reconciled global glacier loss estimates enable a disaggregation of continental land mass changes and a quantification of this term. We found that between 2002 and 2014, climate variability resulted in an additional 3200 ± 900 gigatons of water being stored on land. This gain partially offset water losses from ice sheets, glaciers, and groundwater pumping, slowing the rate of sea level rise by 0.71 ± 0.20 millimeters per year. These findings highlight the importance of climate-driven changes in hydrology when assigning attribution to decadal changes in sea level.

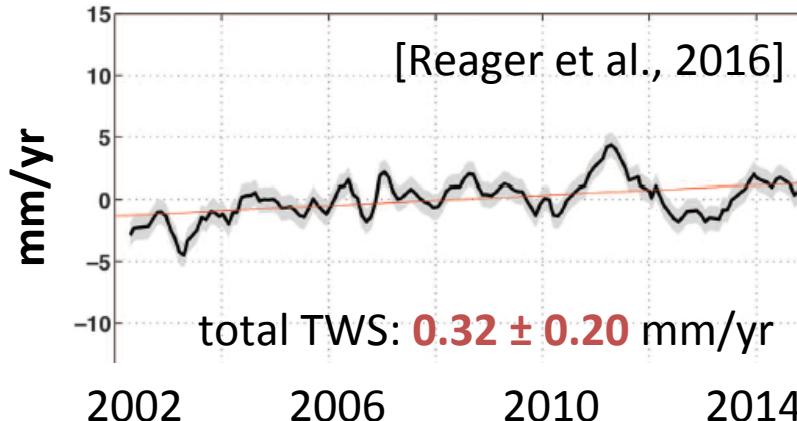
- The strong association with climate-driven variability in precipitation
- Aquifer-depletion also plays a role



Glacier & Land hydrology contributions

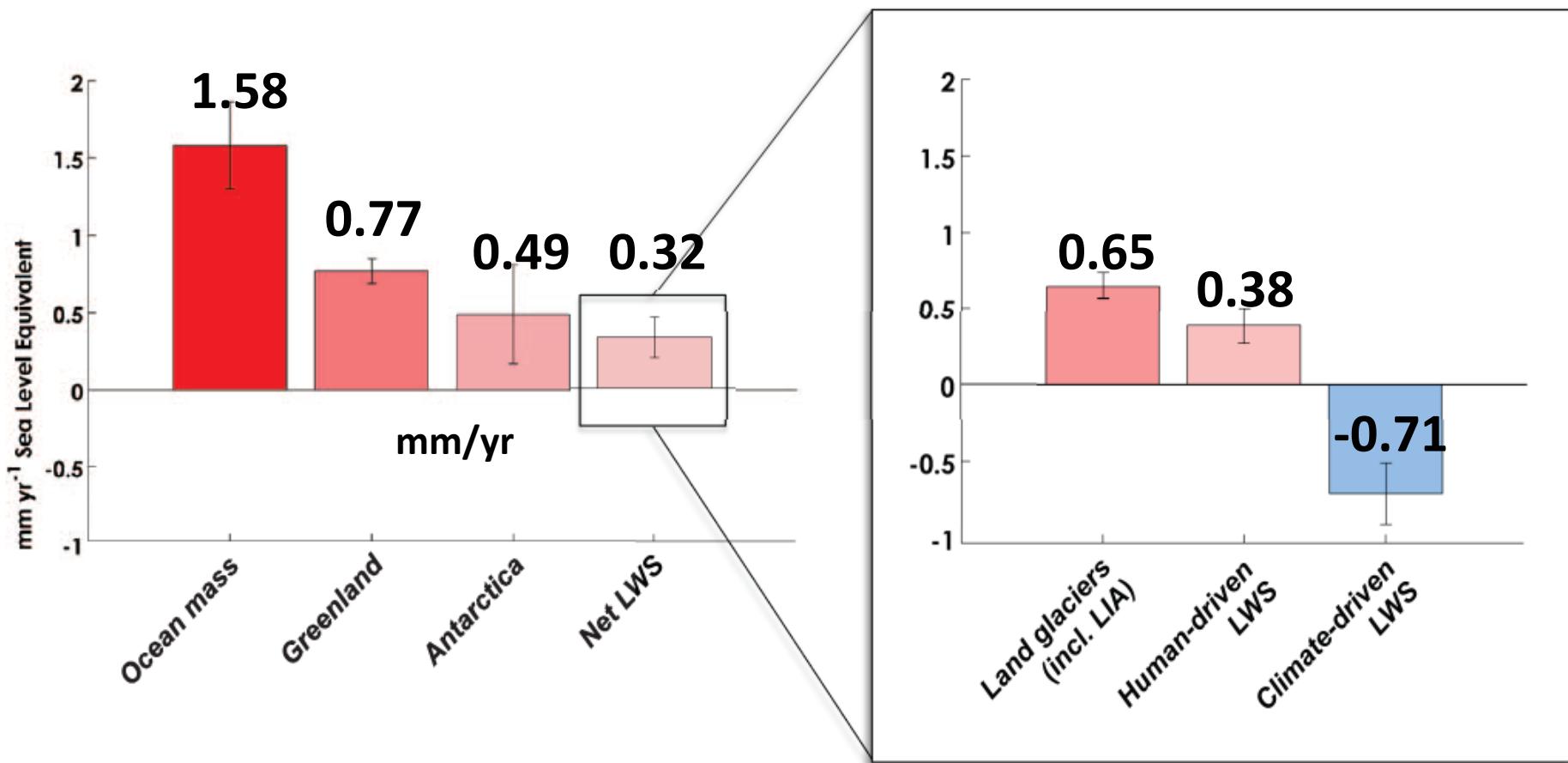


- The strongest gains and losses are associated with climate-driven variability in precipitation
- Aquifer-depletion also plays a role



Glacier & Land hydrology contributions

'Mass sea level' trends (2002 – 2014; mm/yr)



Joint analysis: Sea level & Land Water Storage

[Hamlington et al., 2017]



Altmetric: 3 Views: 478

[More detail >](#)

Article | [OPEN](#)

Separating decadal global water cycle variability from sea level rise

B. D. Hamlington , J. T. Reager, M.-H. Lo, K. B. Karnauskas & R. R. Leben

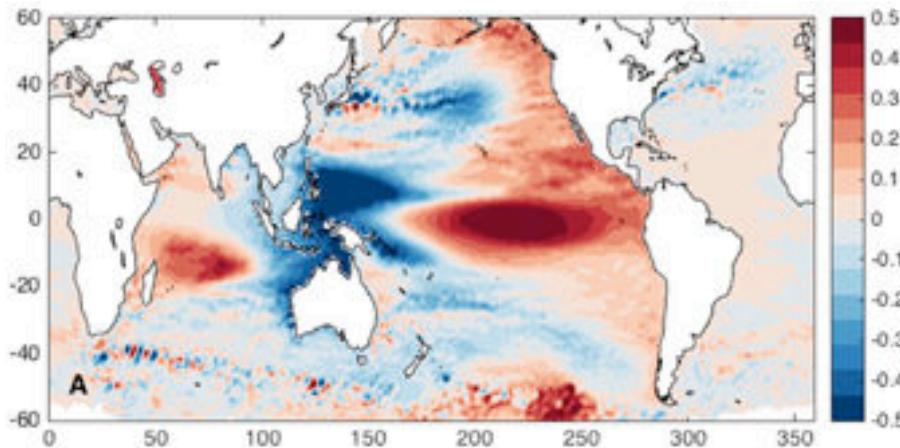


Joint analysis: Sea level & Land Water Storage

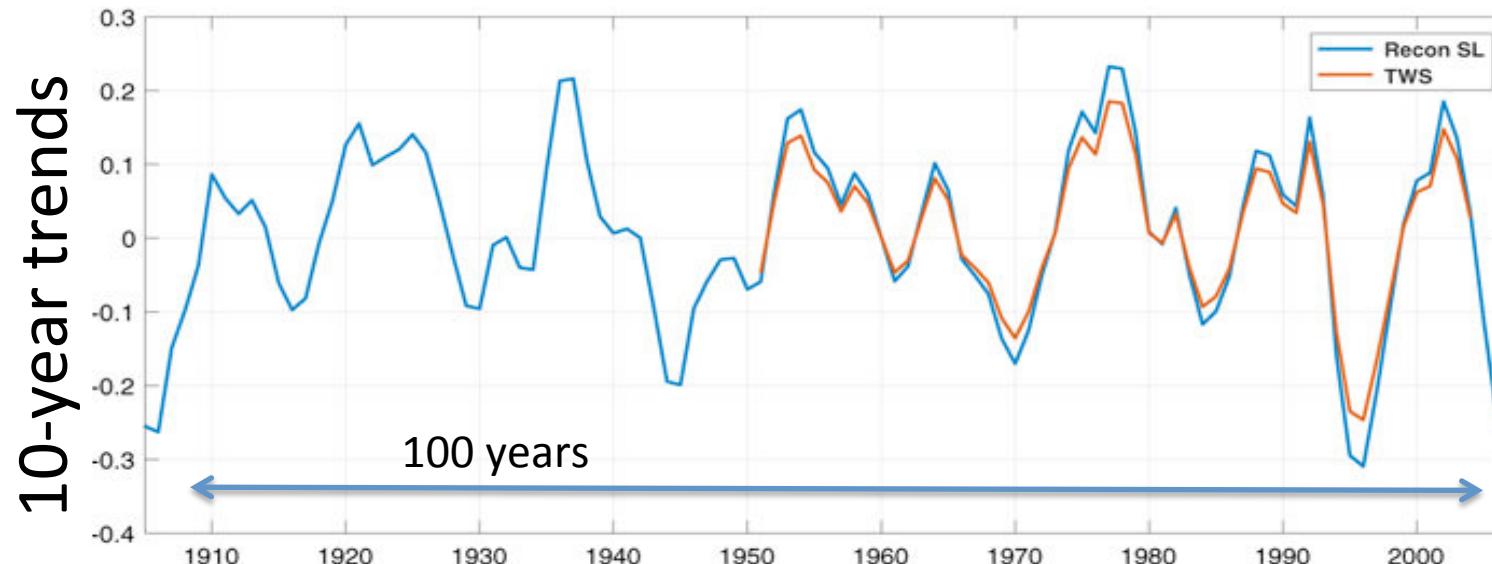
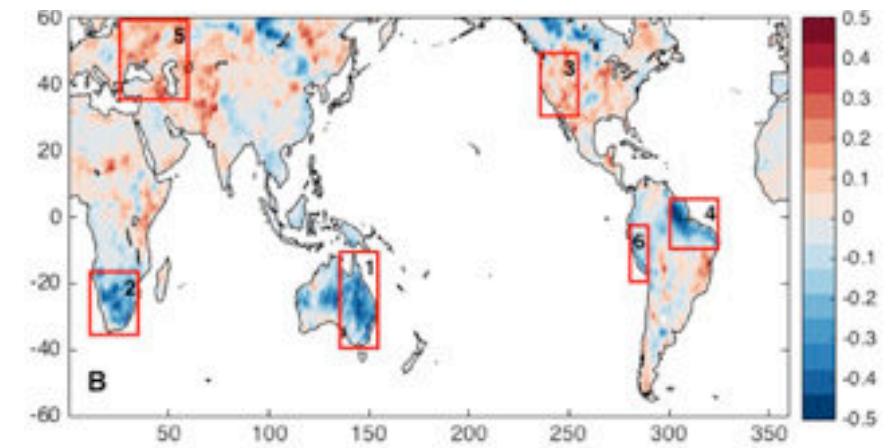
10-year trend patterns (EOF-1; normalized):

[Hamlington et al., 2017]

Sea Level (reconstr)



Land Water storage (GLDAS2)

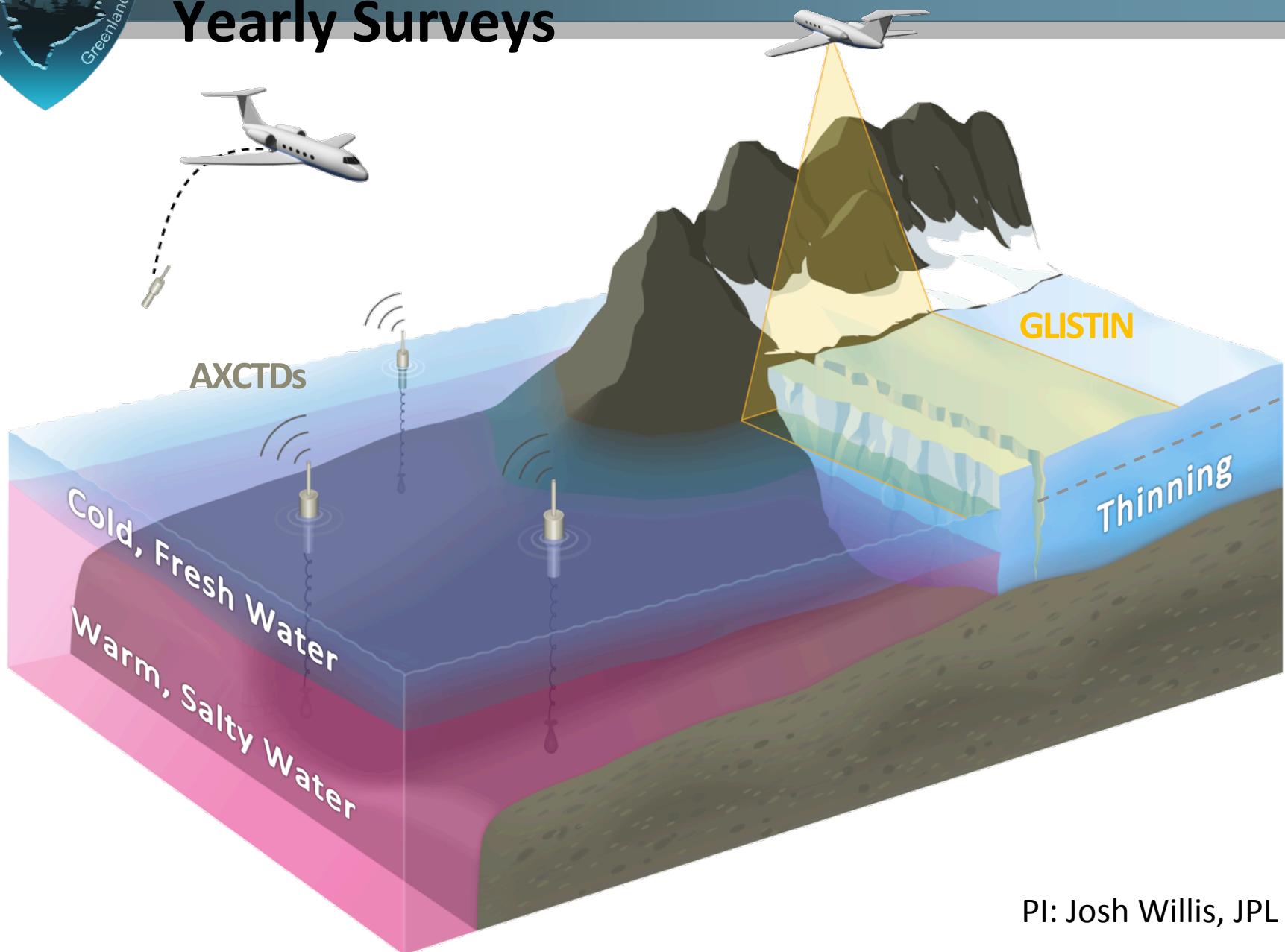


Greenland mass loss (2002-2016)



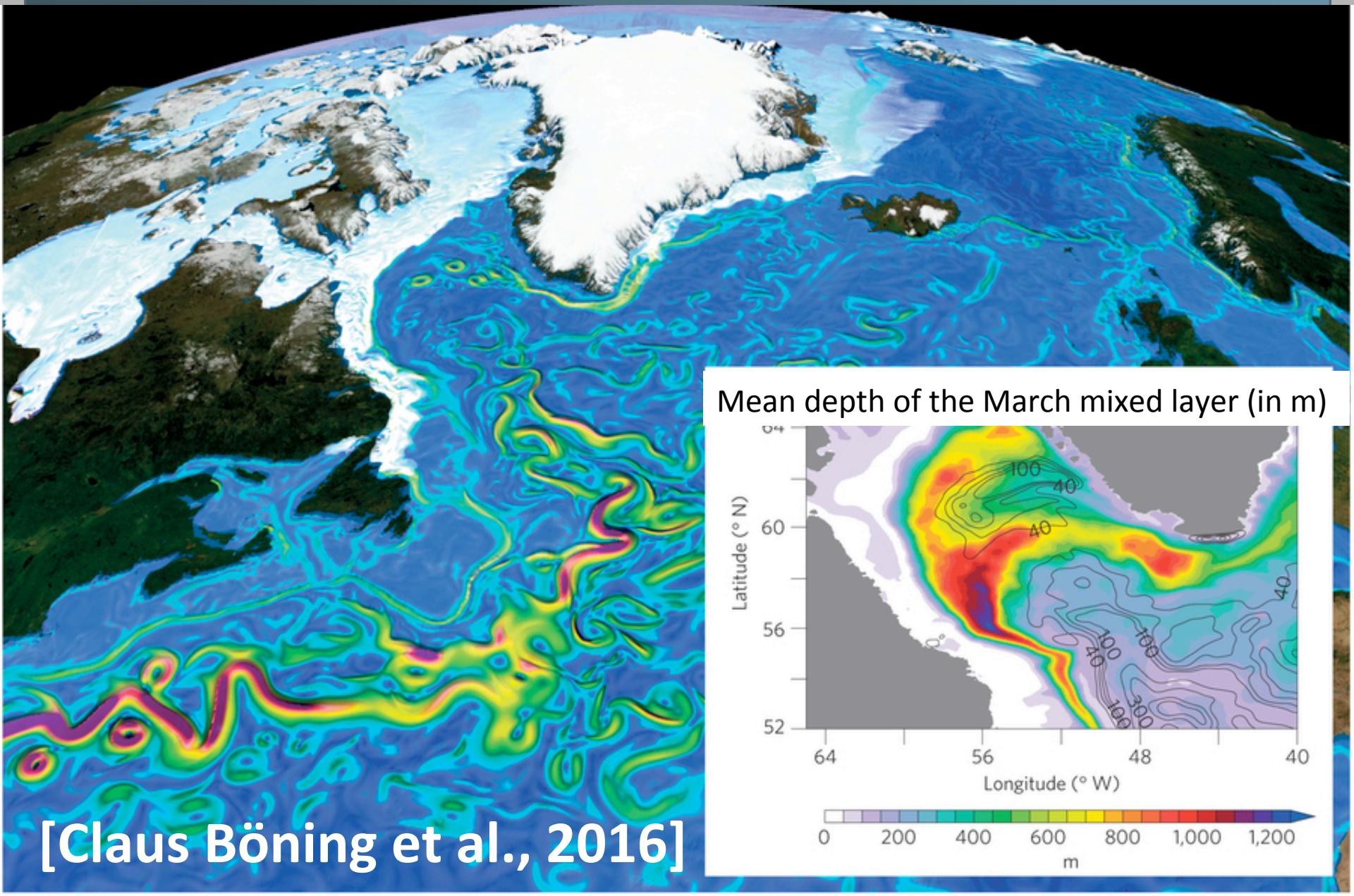


OMG – Oceans Melting Greenland: Yearly Surveys



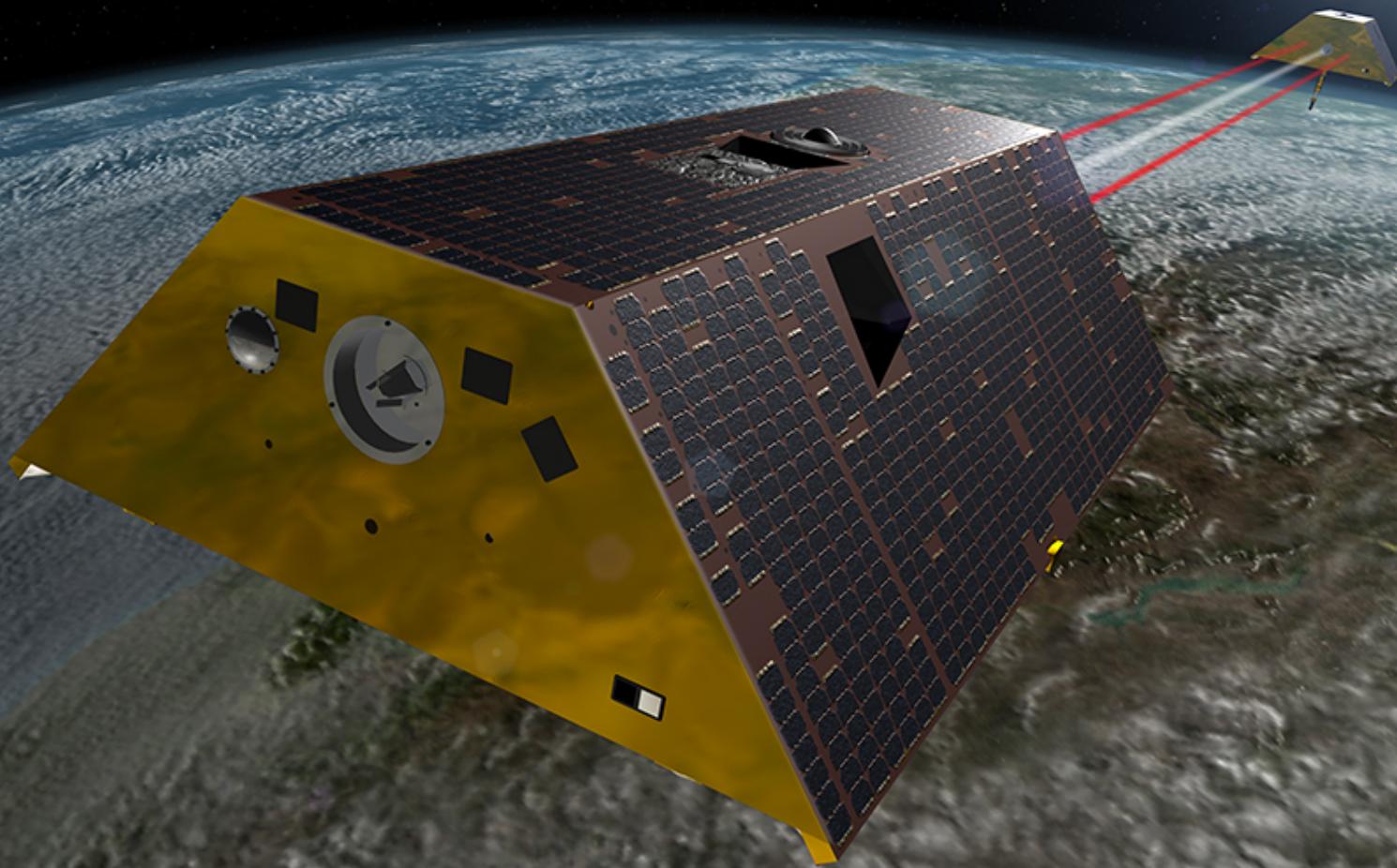
PI: Josh Willis, JPL

Greenland melt: ice \leftrightarrow ocean coupling



GRACE Follow-On

Coming in early 2018!



Summary

- GRACE, altimeters, Argo critical for observing sea level and energy budget
- sea level budget is ‘closed’ in the upper 2000m, but trend biases could easily hide deep warming (blame GIA & geocenter uncertainties!)
- S Pacific: deep warming (<2000m) detected
- GRACE allows a truly global tracking of the water cycle and sub-system exchange
- Land water mass exchange on decadal time scales sizable contributor to sea level
- likely that increased freshwater fluxes will impact ocean circulation (10+ years?)